HIGH-ENERGY EMISSION FROM THE STELLAR WIND COLLISIONS IN γ^2 VELORUM

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ABSTRACT

The binary system γ^2 Velorum (WC8+O7.5) contains the nearest known Wolf-Rayet star to the Sun, at a distance of 258^{+41}_{-31} pc. Its strong radio emission shows evidence for a partially absorbed non-thermal component, which has been interpreted as synchrotron emission from electrons accelerated in the colliding wind region. Inverse Compton cooling of these electrons in the intense UV radiation field from the O-type companion star could produce a significant hard X-ray and γ-ray emission, whose flux depends on the ratio of the energy densities of magnetic to seed photon fields. The Vela region was observed with the *INTEGRAL* satellite in 2003, as part of the Core Programme. No signals from γ^2 Vel are detected in the images obtained with the IBIS/ISGRI coded aperture instrument in the energy ranges 20–40 and 40–80 keV. From the derived 3σ upper limits, we show that the average magnetic field near the region of stellar wind collision should be relatively high, $B \gtrsim 1$ G. The high-energy emission of γ^2 Vel might be detected with the forthcoming *GLAST* experiment.

1. INTRODUCTION

Radio continuum measurements of Wolf-Rayet (WR) stars have revealed at least ten sources with non-thermal (NT) emission, which presumably originates from an interaction between the WR stellar wind and the wind from a massive companion star (Chapman et al. 1999, and references therein). The observed NT radio spectra and luminosities are well explained as synchrotron emission from relativistic electrons accelerated at strong shocks in the colliding wind region (Eichler and Usov 1993).

Benaglia and Romero (2003) have recently studied the production of γ-ray emission in the binary systems WR 140, WR 146 and WR 147. They showed that inverse Compton (IC) scattering of the accelerated electrons in the strong photon fields of the early-type stars could produce γ-ray fluxes above the *INTEGRAL*/IBIS continuum sensitivity. In the case of WR 140, they also showed that the expected high-energy emission can account for the unidentified EGRET source 3EG J2022+4317.

In the present paper, we consider the relatively close (i.e. with short orbital period P_{orb}=78.53 days) binary system γ^2 Velorum (=WR 11, van der Hucht 2001). With a distance of 258^{+41}_{-31} pc, as determined from *Hipparcos* parallax measurements, this WC8+O7.5 binary contains the nearest WR star to the Sun. Radio and millimetre observations of γ^2 Vel essentially revealed the strong thermal emission from the WR ionized wind (e.g. Leitherer et al. 1997). However, Chapman et al. (1999) found a significant steepening of the radio spectral index between 3 and 20 cm, which they interpreted as evidence for a highly attenuated NT component originating in the colliding wind region, well within the radio photosphere of the WR star (Chapman et al. 1999). This contrasts with the wider binary systems studied by Benaglia and Romero (2003), for which the free-free absorption of the NT radio emission by the WR wind is less important.

The existence of strong shocks in the colliding wind region of γ^2 Vel is also supported by X-ray observations (Skinner et al. 2001, and references therein). In particular, *ROSAT* and *ASCA* data have revealed a hot plasma emission ($kT \gtrsim 1$ keV) with a strong phase-locked variability, which was interpreted as a colliding wind shock emission originating deep within the dense and opaque WR wind, and showing significantly less photoelectric absorption at orbital phases when the cavity around the O-type companion star crosses the line of sight (Rauw et al. 2000, and references therein).

The model for the high-energy emission from the stellar wind collisions in γ^2 Vel is described in the next section. In Sect. 3, we present the *INTEGRAL*/IBIS observations. The results are discussed in Sect. 4.

2. HIGH-ENERGY EMISSION MODEL

2.1. The Stellar Parameters and the Geometry of the System

The geometry of the region of stellar wind collision in a close binary is described by Eichler and Usov (1993). Assuming the collision of two spherical winds, the distances r_{WR} and r_O from the WR and O-type stars, respectively, to the region where the winds interact is

$$r_{WR} = \frac{1}{1+\eta^{1/2}} D_{bin} \quad \text{and} \quad r_O = \frac{\eta^{1/2}}{1+\eta^{1/2}} D_{bin}. \tag{1}$$

Here D_{bin} is the distance between the two stars and η denotes the ratio of the wind momentum fluxes of the O star to the WR star:

$$\eta = \frac{\dot{M}_O V_O^\infty}{\dot{M}_{WR} V_{WR}^\infty}, \tag{2}$$

where $\dot{M}_i$ and V_i^∞ are the mass-loss rate and the wind terminal velocity of the star i, respectively.

Stellar and orbital elements of γ^2 Vel are given in Table 1. These parameters have been obtained after the revised distance determination with the *Hipparcos* satellite (Schaerer et al. 1997). From the derived mass-loss rates and wind terminal velocities, we get from eq. (2) η=0.032, such that the colliding wind region is very close to the surface of the O star (eq. 1): as D_{bin} varies from 0.82 to 1.60 AU in this eccentric binary, r_O is contained between $2.1R_0$ (at periastron) and $4.2R_0$ (at apastron), where R_0=12.4 R$_\odot$ is the radius of the O-type star. In this environment, electrons accelerated at the strong shocks formed by the colliding stellar winds, should produce, together with the observed NT synchrotron radiation, a significant hard X-ray and γ-ray emission by IC interactions with UV photons emitted by the O star. The flux of high-energy emission relative to the NT radio emission depends essentially on the ratio of the energy densities of magnetic to seed photon fields.

Table 1. Stellar and orbital parameters of γ^2 Vel.

Parameters	WR star	O star
$\dot{M}$ (M$_\odot$/yr)	$9.3\times10^{-6(a)}$	$1.83\times10^{-7(a)}$
V^∞ (km/s)	$1550^{(a)}$	$2500^{(a)}$
R (R$_\odot$)	$3.2^{(a)}$	$12.4^{(a)}$
$\log(L/\mathrm{L}_\odot)$	$5.00^{(a)}$	$5.32^{(a)}$
T_{eff} (K)	$57100^{(a)}$	$35000^{(a)}$
Distance		258 pc$^{(b)}$
Orbital period		78.53 days$^{(b)}$
Semi-major axis		1.21 AU$^{(c)}$
Eccentricity		$0.326^{(c)}$
$\Rightarrow$ Binary separation D_{bin}		0.82–1.60 AU
NT radio spectral index α		$-0.5^{(d)}$
S$_{4.8\ \mathrm{GHz}}$		13.5 mJy$^{(d)}$

[a] De Marco et al. (2000); [b] van der Hucht (2001); [c] Schmutz et al. (1997); [d] Chapman et al. (1999).

2.2. The Magnetic Field in the Stellar Wind Collision Zone

However, the strength of the magnetic field near the colliding wind region is not well-known. Following Eichler and Usov (1993), it may be estimated from the expected geometry of the magnetic field in an outflowing stellar wind as

$$B(r) = B^s \times \begin{cases} \left(\frac{R}{r}\right)^3 & \text{for } R \le r < r_A \text{ (dipole)}, \\ \frac{R^3}{r_A r^2} & \text{for } r_A < r < R\frac{V^\infty}{V^{rot}} \text{ (radial)}, \\ \frac{V^{rot}}{V^\infty}\frac{R^2}{r_A r} & \text{for } r > R\frac{V^\infty}{V^{rot}} \text{ (toroidal)}, \end{cases} \tag{3}$$

where R is the radius of the star, B^s its surface magnetic field, $V^{rot}\sim(0.1\text{–}0.2)V^\infty$ its surface rotation velocity and $r_A\sim(1\text{–}3)R$ the Alfvèn radius. For $B^S_{WR}\sim$0.1–10 kG (e.g. Maheswaran and Cassinelli 1994) and $B^S_O \lesssim 100$ G (e.g. Charbonneau and MacGregor 2001), we obtain $B\sim$0.1–10 G in the NT emission zone. It is possible that the average magnetic field is enhanced by the compression produced by the strong shocks in the region of the stellar wind collision.

2.3. The Nonthermal Emissions

In the vicinity of the O star, energy losses of the accelerated electrons are mainly due to IC scattering. Coulomb and Bremsstrahlung losses can safely be neglected, as well as synchrotron losses if the average magnetic field $B \lesssim 50$ G. In the steady state approximation, the equilibrium spectrum of the fast electrons is then given by

$$N(E_e) = \frac{1}{\dot{E}_{IC}(E_e)} \int_{E_e}^{\infty} \dot{Q}(E'_e) \times \exp\left[- \int_{E_e}^{E'_e} \frac{dE''_e}{t_{esc}\dot{E}_{IC}(E''_e)} \right] dE'_e \ , \tag{4}$$

where $\dot{Q}(E_e)$ is the differential injection rate of electrons accelerated at the shocks, $t_{esc}\sim\pi r_O/c$ is the average time spent by the fast electrons in the NT emission region (c is the speed of light) and

$$\dot{E}_{IC}(E_e) \cong \frac{4}{3}\sigma_T U_O \left(\frac{E_e}{m_e c^2}\right)^2 \tag{5}$$

is the IC energy loss rate, with σ_T the Thomson cross section, m_e the electron mass and

$$U_O = \frac{L_O}{2\pi c R_O^2}\left[1 - \cos\{\arcsin(R_O/r_O)\}\right] \tag{6}$$

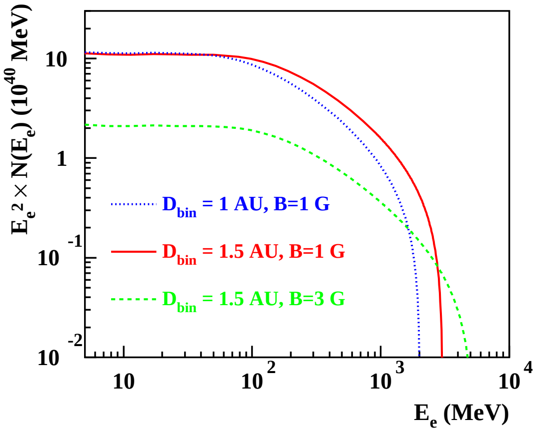

Figure 1. Electron equilibrium spectra (times E_e^2) for 2 values of the binary separation D_{bin} and average magnetic field B. All spectra are normalized to the production of the observed synchrotron flux density $S_{4.8\ \mathrm{GHz}}$=13.5 mJy (see Table 1).

the energy density of radiation from the O star in the NT emission region.

We assumed the source spectrum of the accelerated electrons to be of the form

$$\dot{Q}(E_e) \propto E_e^{-s} \quad \text{for } E_e < E_{max}, \tag{7}$$

where the maximum energy E_{max}=$\gamma_{max} m_e c^2$ is obtained from the condition that the IC loss rate not exceed the acceleration rate (Eichler and Usov 1993):

$$\gamma_{max}^2 \simeq 3 \times 10^8 \eta \left(\frac{V_{WR}^{\infty}}{2 \times 10^8\ \mathrm{cm\ s^{-1}}}\right)^2 \left(\frac{B}{G}\right) \times \left(\frac{D_{bin}}{10^{13}\ \mathrm{cm}}\right)^2 \left(\frac{L_O}{10^{39}\ \mathrm{erg\ s^{-1}}}\right)^{-1}. \tag{8}$$

The power-law spectral index s is related to the one of the radio synchrotron emission α=-0.5 (Table 1) by the classical formula α=$-(s-1)/2$. We thus have s=2, which is appropriate for strong shock acceleration.

Calculated electron equilibrium spectra are shown in Fig. 1. We see that for reasonable values of the binary separation and average magnetic field near the region of stellar wind collision, the electron energy distributions are cut off at a few GeV. In comparison, the electrons accelerated in the wider binary systems WR 140, WR 146 and WR 147 can reach energies of hundreds of GeV and thus produce IC emission at higher energies than for γ^2 Vel (Benaglia and Romero 2003).

Multi-band emission spectra are shown in Fig. 2. Synchrotron and IC radiations of fast electrons having the equilibrium spectra shown in Fig. 1 were calculated from the detailed formalisms of Blumenthal and Gould (1970). The ASCA upper limit has been derived from the observations of Rauw et al. (2000). These authors have detected a relatively hard emission component with strong variability over the binary orbital cycle, which they interpreted as the thermal emission from the shocked plasma in the colliding wind region. The intrinsic (absorption-corrected) luminosity of this component in the 0.5–10 keV energy range is $\gtrsim 10^{32}$ erg s^{-1}. Since the X-ray emission does not show evidence for a NT component, we used this value to derive the upper limit shown in Fig. 2.

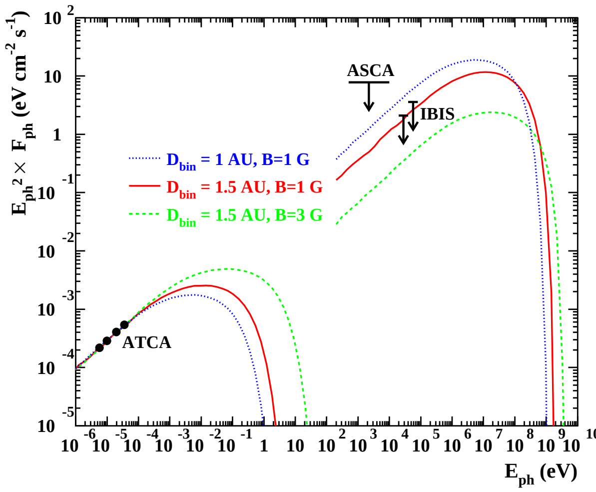

Figure 2. Multi-band emission spectra (times E_{ph}^2) for the same values of the binary separation D_{bin} and average magnetic field B as in Fig. 1. Also shown are the NT radio data at 3, 6, 13 and 20 cm obtained with ATCA (Chapman et al. 1999), the upper limit on the 0.5–10 keV NT emission derived (see text) from ASCA observations (Rauw et al. 2000) and the INTEGRAL/IBIS upper limits (Sect. 3).

There is no point-like source in the third *CGRO*/EGRET catalog which is positionally coincident with γ^2 Vel (Hartman et al. 1999). But because the energy of the accelerated electrons is limited to a few GeV, the predicted fluxes of the IC emission are exponentially cut off at $\sim$100 MeV, i.e. just above the low-energy threshold of the EGRET experiment. Furthermore, the detection of high-energy γ-ray emission from γ^2 Vel could be complicated by the proximity of the Vela pulsar, which is on time-average the brightest high-energy source in the sky (the angular separation of γ^2 Vel and the Vela pulsar is 4.9°, whereas the FWHM of the EGRET point spread function at 100 MeV is $\sim$6°). In fact, the third EGRET catalog contains 6 sources in the Vela region, which are almost certainly artefacts associated with the intense emission from the Vela pulsar (Hartman et al. 1999). This makes it very difficult to obtain a statistically meaningful upper limit for the high-energy IC emission of γ^2 Vel.

3. INTEGRAL/IBIS OBSERVATIONS

INTEGRAL observations of the Vela region were performed in the dithering mode of the satellite, on

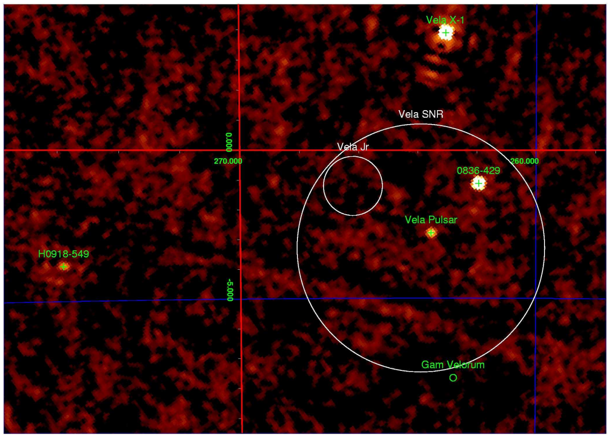

Figure 3. IBIS/ISGRI significance map of the Vela region in the 20-40 keV energy band. The circles show the positions of the two supernova remnants.

2003 June 12–July 6 (fragmented observations) and November 27–December 11. The total exposure time amounts to $\sim 1.4\times10^6$ s. The two observations were obtained when the binary was near apastron (from the ephemeris determined by Schmutz et al. 1997). During the two INTEGRAL observations, the average distance between the two stars was $D_{bin}\simeq 1.5$ AU. In comparison, the ATCA radio data were taken when the system was near periastron, for an average binary separation $D_{bin}\simeq 1$ AU.

No signals from γ^2 Vel are detected in the images obtained with the IBIS/ISGRI coded aperture instrument in the energy ranges 20–40 keV (Fig. 3) and 40–80 keV. The 3σ upper limits obtained from the instrument sensitivity are 7.4×10^{-5} and 6.4×10^{-5} photons cm^{-2} s^{-1} in the 20–40 and 40–80 keV energy ranges, respectively.

4. RESULTS AND DISCUSSION

The high-energy IC radiation of γ^2 Vel, which should accompany the synchrotron radio emission revealed by the ATCA data, is not detected with IBIS/ISGRI. A possible explanation is that the average magnetic field near the region of stellar wind collision is relatively high. Assuming that the intrinsic NT radio emission does not significantly vary over the orbital cycle, we obtain from the IBIS/ISGRI 3σ upper limits $B \gtrsim 1$ G (see Fig. 2). However, a significant variation of the NT radio emission is observed in the well-studied binary WR 140. From 8 years of monitoring the radio flux of WR 140 with the VLA, White and Becker (1995) have shown that the intrinsic NT component (before attenuation by free-free absorption) seems to become weaker near periastron, which is not expected in the model of spherically symmetric colliding winds. They proposed a new model in which the WR wind is strongly enhanced in the star equatorial disk. Such an effect could exist in the eccentric binary γ^2 Vel as well, and radio and γ-ray observations at the same orbital phases are required to specify the parameters of stellar wind collisions.

The forthcoming γ-ray telescope *GLAST* might detect the $\gtrsim 20$ MeV IC emission of γ^2 Vel, provided that the proximity of the very bright Vela pulsar does not induce a contamination problem. For an estimated 3σ sensitivity $S_{ph}\times E_{ph}^2 \sim 0.4$ eV cm^{-2} s^{-1} at 100 MeV (for one year of observation and $\Delta E_{ph}=E_{ph}$), the IC counterpart of the NT radio emission could be observed if the average magnetic field near the colliding wind zone is $B \lesssim 10$ G (see Fig. 2). In the case of a positive detection, it casts no doubt that γ^2 Vel would become a key object for understanding the processes of particle acceleration in binaries of early-type stars.

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